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Updating the United States Government's Social Cost of Carbon

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Abstract

Since its release in 2010, the United States government's Social Cost of Carbon (SCC) has played a central role in climate policy both domestically and internationally. However, rapid progress in climate science and economics over the last decade mean that it is no longer based on the frontier of understanding. Specifically, extensive new research about the climate, economy, and their relationship has altered understanding about the magnitudes of the projected physical and economic impacts of climate change, as well as their heterogeneity across space and time. This paper provides concrete recommendations on how to rebuild the SCC based on these new advances and return it to the scientific frontier.

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I. Introduction

Across the world, climate policies have the potential to provide large benefits by reducing the harms resulting from carbon dioxide (CO_2) emissions. However, these policies can be costly, with some more expensive than others. The value of reducing emissions is not $0, nor is it infinite. Some imaginable fuel economy standards, for example, would be stringent, while others would be lenient. What level of stringency is optimal, if those standards aim to reduce carbon dioxide emissions?

A key tool in identifying such policies is the social cost of carbon (SCC),[1] which measures the monetized value of *all* future net damages associated with a one metric ton increase in CO_2 emissions.[2] The SCC therefore provides a measure of how much society should be willing to pay for a one-ton reduction in CO_2 emissions and allows policymakers to conduct a comparison of a regulation's benefits and costs, both measured in dollars. From the standpoint of law and practice, this conversion of CO_2 emissions into dollars is extraordinarily helpful. In the United States, some legislation requires agencies to conduct cost-benefit analysis, and prevailing Executive Orders, supported by both Republican and Democratic presidents, require such an analysis for all major regulations, including those designed to reduce carbon emissions. In contrast, other proposed approaches for climate policy evaluation, such as defining a temperature target and identifying cost-minimizing policies to achieve it, do not have strong legal footing (Sunstein, forthcoming), and replace scientific assessment of costs and benefits with politically-based rules (Aldy et al., 2021).

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[1] For the remainder of paper, we will refer to the SCC, but this encompasses the social cost of carbon, as well as of methane and nitrous oxides, which are calculated with the same approach.

[2] In theory, the SCC captures *all* future net damages associated with a marginal increase in CO_2 emissions, but in practice measuring all damages is challenging, as discussed throughout the text.

Following the Supreme Court's decision in *U.S. Environmental Protection Agency (EPA) vs. Massachusetts (2007),* the U.S. government has been required to issue at least some regulations to reduce greenhouse gas emissions, but at the time of the decision it lacked a consistent SCC with which to inform its judgments. In 2009, the Obama Administration issued a temporary SCC and formed an Inter-agency Working Group (IWG) tasked with developing a robust SCC, based on the best available science and economics. The work was completed in 2010 and successively updated, ultimately producing a value of $51 per ton of CO_2 in 2020 (IWG, 2013). The same methods were used to develop a social cost of methane and of nitrous oxides, other potent greenhouse gases, in 2016 (IWG, 2016).

Since its release in 2010, the SCC has played a central role in climate policy both domestically and internationally. As of 2017, the federal government had used the SCC to assess the value of over eighty regulations with a combined $1 trillion in estimated gross benefits (Nordhaus, 2017). At least eleven state governments use an SCC to guide policy, most notably Illinois and New York, where the SCC is used to value "zero-emissions credits" paid to clean energy producers. Meanwhile, several other countries, including Canada, France, Germany, Mexico, Norway, and the United Kingdom, have referred to the experience of the United States to implement their own SCC estimates, with some adopting estimates wholesale from the IWG. Further, the national SCC can also influence international climate negotiations: experience demonstrates that meaningful U.S. climate action can leverage large reductions in emissions from other countries, reducing the climate damages facing Americans (Houser et al., 2021).

Several events make clear that updating the SCC is critically important. First, over the last dozen years, new research has dramatically altered understanding about the magnitudes of the projected physical and economic impacts of climate change, as well as their heterogeneity across space and time. These advances rely on large-scale datasets and greatly reduce the need to rely on unverifiable assumptions. Figure 1 demonstrates that this new empirically-grounded research has reached fundamentally different conclusions about the sector-specific components or "partial" SCCs (blue) for energy demand, mortality risk, labor disutility, and agricultural productivity (Carleton et al., 2021; Rode et al. 2021a,b; Moore et al., 2017), when compared to partial SCCs from the FUND model, one of three IAMs behind the IWG SCC. Indeed, the original IWG called for updating the SCC regularly to reflect advances in understanding (IWG, 2010) and the National Academies of Sciences, Engineering, and Medicine (NASEM) confirmed this seven years later (NASEM, 2017).

Second, this new research finds that climate change impacts are much more heterogeneous than previously assumed, and this heterogeneity matters for damage valuation. For example, Hsiang et al. (2017) find that climate change is projected to cause economic damages in the poorest 5 percent of U.S. counties that are approximately nine times larger by the end of the century than those experienced in the richest 5 percent. Additionally, Carleton et al. (2021) find large differences in the projected change in mortality risk both across and within countries globally. Importantly, these advances make it possible to characterize *who* is most affected by climate policies—insight that is out of reach under the current SCC framework— and to incorporate this heterogeneity into the valuation of climate change impacts.

Third, the legal durability of the SCC requires that it be based on frontier science and economics. This was underscored in 2020 when a federal district judge struck down a Trump Administration rollback of methane emissions standards pointing to its social cost of methane calculation as "riddled with flaws", characterizing it as "arbitrary" and "capricious" (*California v. Bernhardt*, 2020). The overturned calculation was not justified based on science and economics (Greenstone 2019) and reduced the SCC to between $1 and $8 (Figure 1). Nonetheless, it provided the basis for weakening a wide variety of environmental regulations beyond the methane rule (Supplementary Materials Figure S1).

This paper outlines how the SCC can be revised to once again be at the frontier of knowledge. There are seven key "ingredients" that should go into such a process. The next section identifies each of them, explains what was done in the past, describes how understanding has advanced since 2009-2010, and makes specific recommendations. The final section details an implementation pathway for combining these ingredients into an updated SCC. Taken together, the paper provides a potential framework for the Biden Administration, which has committed to comprehensively updating the SCC by early 2022 (IWG, 2021).

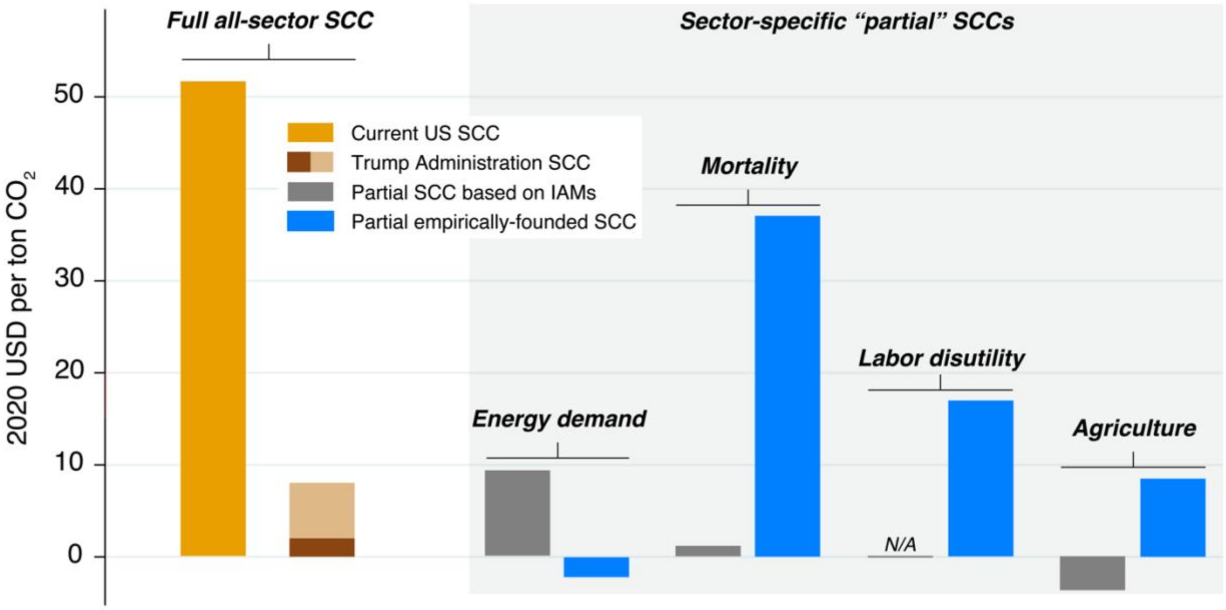

Figure 1: Current U.S. Social Cost of Carbon (SCC) is behind frontier science. Figure compares current and past U.S. federal SCCs to those produced by recent research. The all-sector SCCs shown on the left include values used by the Trump Administration (brown) and the interim estimate under the Biden Administration (gold). Sector-specific "partial" SCCs on the right come from the Interagency Working Group 2013 implementation of the FUND model (one of the three models used to derive the U.S. federal all-sector SCC; grey) and recent scientific literature

(blue). *Sources:* Rode et al. (2021a,b), Carleton et al. (2021), Moore et al. (2017), and Anthoff and Tol (2014), decomposed by Diaz (2014). Estimates represent the 2020 SCC under either "business-as-usual" emissions (FUND IAM partial SCCs and agriculture partial SCC), an emissions ensemble with 4/5 weight placed on "business-as-usual" scenarios (all-sector SCCs), or a high emissions scenario (RCP 8.5; mortality, labor, and energy partial SCCs). Socioeconomic scenarios vary and reflect each author's central estimate. Discount rates differ across authors and administrations; the Trump Administration's 3 percent (light brown) to 7 percent (dark brown) range is shown. Estimates are converted to USD 2020 using the annual GDP Implicit Price Deflator in the U.S. Bureau of Economic Analysis' National Income and Product Accounts Table 1.1.9.

II. The Seven Key Ingredients for a Revised SCC

Calculating the SCC requires a model that accounts for future economic growth, the relationship between emissions and climate change, the effect of climate change on the economy, and multiple other factors. Such models are referred to as Integrated Assessment Models (IAMs), since they combine scientific and economic models to evaluate the impacts of carbon emissions. The Obama-era IWG estimated the SCC using three IAMs—DICE, FUND, and PAGE—which were developed in the 1990s and have been widely used in the economic and scientific literature (Nordhaus, 2010; Anthoff and Tol, 2014; Hope 2011).

There are seven "ingredients" necessary to construct the SCC. The first four are sometimes referred to as "modules" (Figure 2):

1. Socioeconomic and emissions trajectories, which predict how the global economy and CO_2 emissions will grow in the future;
2. A climate module, which measures the effect of emissions on the climate;
3. A damages module, which translates climate changes into economic damages; and

4. A discounting module, which calculates the present value of future damages.

Three additional cross-cutting modeling decisions affect the entire process:

1. Whether to include global or only domestic climate damages;
2. How to value uncertainty; and
3. How to treat equity.

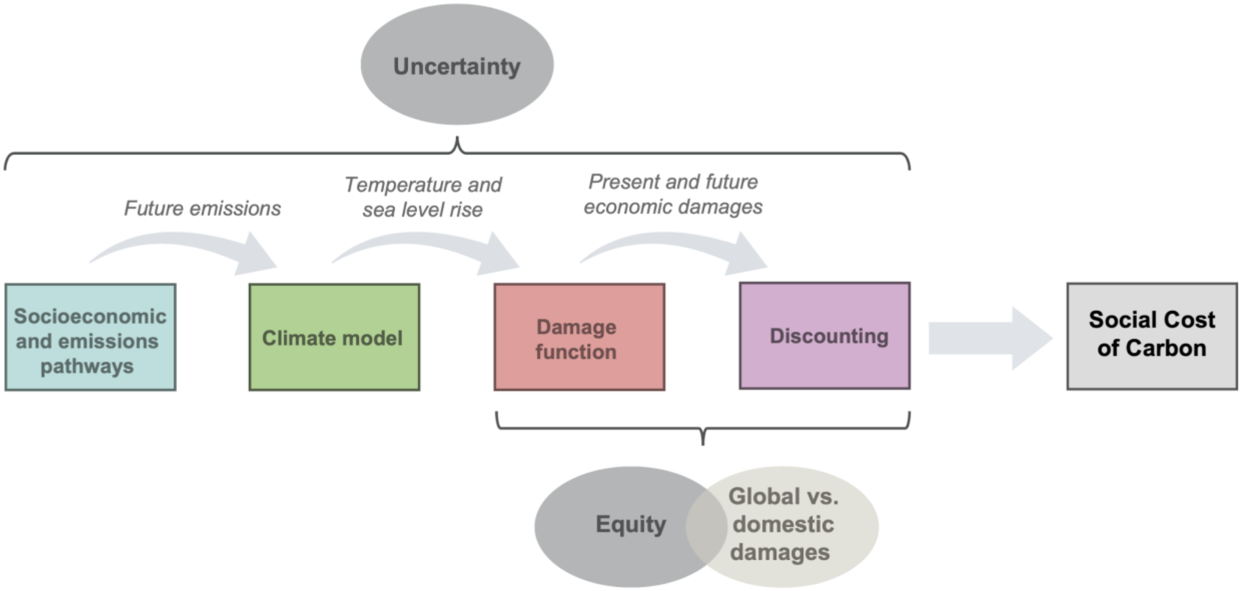

Figure 2: Seven ingredients for calculating the Social Cost of Carbon. Figure displays the four "modules" that compose the SCC (colored boxes), and the three key modeling decisions (grey ovals) that together form the seven "ingredients" necessary to compute an SCC.

Updating the SCC so that it is built on a foundation of best available science and economics requires a new IWG to make decisions regarding each of these seven ingredients. However, some required updates are already clear. Due to significant advances in climate modeling and in climate impact analysis, as well as profound changes in global capital markets, it is *essential* to update the climate and damage modules and to change the discount rate. There is additionally a very strong case to reflect global, as opposed to domestic only, damages, based on an overwhelming consensus amongst scientific and economic experts. Failing to account for these advances would leave any new SCC open to well-founded scientific criticism and vulnerable to legal invalidation. There are also valuable opportunities to update the other three ingredients, but to varying degrees the scientific and/or policy case for doing so is not as decisive.

This paper can be thought of as a "recipe," outlining ways to bring the U.S. government's SCC back to the scientific frontier. This section briefly explains each of the seven key ingredients, describes how they were handled by the IWG in 2010, and makes recommendations to update each.

A. Essential Updates to the SCC

Ingredient One: Climate Module

Background: Any SCC calculation requires a climate model that converts carbon emissions into changes in the global climate. Specifically, these models characterize the relationship between emissions, atmospheric CO_2 concentrations, and changes in the climate, including warming and sea level rise. All three IAMs used by the IWG included highly simplified climate models. A core input into each was the Equilibrium Climate Sensitivity (ECS), which determines the total global warming realized from a doubling of atmospheric carbon concentrations. The ECS has a substantial impact on the SCC, but its true value is not known with scientific certainty.

2010 IWG Approach: The IWG relied on the climate models within each IAM. To ensure that the ECS values used reflected best available science, the IWG harmonized the ECS across all models by using a probability distribution reflecting the likelihood of different possible climate outcomes at the end of the century according to the Intergovernmental Panel on Climate

Change's (IPCC) Fourth Assessment Report. This was the only component of each IAM's climate model that the IWG calibrated to match scientific evidence.

Progress: Recent evidence makes clear that these IAMs, even with a harmonized ECS, are outdated, as they do not accurately quantify multiple links in the causal chain from emissions to temperature change (Dietz et al., 2020; Hänsel et al., 2020; Montamat and Stock, 2020; NASEM, 2017). In particular, DICE, FUND, and PAGE substantially underestimate the *speed* of warming, relative to climate models that satisfy the NASEM criteria for meeting scientific standards (Montamat and Stock, 2020). For example, higher atmospheric CO_2 concentrations cause the oceans to warm and acidify, which makes them less effective at removing CO_2 from the atmosphere. The consequence is a positive feedback loop that accelerates warming (Dietz et al., 2020). This dynamic is missing from both DICE and PAGE (Figure S2).

The fact that existing IAMs do not reflect well-developed climate science literature substantially influences the SCC (Dietz et al., 2020). Importantly, the delayed warming in the IAMs results in SCCs that are likely too low. The delay pushes warming further into the future, which is discounted more heavily, as shown in the bottom panel of Figure S2.

Recommendation: It is vital that an updated SCC rely on an accurate characterization of the climate system. Because any SCC calculation requires fully capturing climatological uncertainty, however, it would be computationally infeasible to replace IAM climate models with state-of-the-art Earth system models that capture the physics, chemistry, and biology of the atmosphere, oceans and land at high spatial resolution. Therefore, a simple Earth system model that can conduct uncertainty analysis while also matching predictions from these more complex models is necessary.

We recommend that the simple Earth system model Finite Amplitude Impulse Response (FAIR) (Millar et al., 2016) be used to project changes in temperature.[3] The FAIR model satisfies all criteria set by the NASEM for use in an SCC (NASEM, 2017). Importantly, this model generates projections of warming consistent with comprehensive, state-of-the-art models *and* it can be used to characterize uncertainty regarding the impact of an additional ton of CO_2 on global mean surface temperature (GMST). Finally, FAIR is easily implemented, transparently documented,[4] and is already being used in SCC updates (Carleton et al., 2021; Dietz et al. 2020; Hänsel et al., 2020; Rode et al., 2021a,b).

A key limitation of simple climate models like FAIR is that changes in global mean sea level rise (GMSL) are not represented. However, Kopp et al. (2016) and others have built semi-empirical models that enable the inclusion of damages due both to warming *and* to projected sea level changes. A limitation of these models is that they may underestimate sea level rise due to their inability to capture plausible future dynamics (e.g., ice cliff collapse) that are not observed in the historical record.

We additionally recommend that semi-empirical models be used to project changes in sea level based on changes in global mean surface temperature from FAIR.

Ingredient Two: Damages Module

Background: A "damage function" translates physical climate changes (e.g., temperature and sea level rise) into monetized economic impacts. In some IAMs, a single damage function is calibrated to represent all categories of impact (e.g., PAGE), while in others, separate damage

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[3] See Supplementary Materials S.I for a discussion of how to combine climate projections from FAIR with high spatial resolution damage estimates.

[4] FAIR's source code can be accessed here: https://github.com/OMS- NetZero/FAIR/.

functions are modeled for individual impact categories (e.g., FUND). In DICE, a single damage function is used, but it is based on sector-specific damage estimates (Nordhaus, 1992).

The IAM damage functions behind the current U.S. SCC have at least two key problems. First, they are primarily derived from ad-hoc assumptions and simplified relationships that were necessary in the 1990s when computing power and data access were less mature than they are now. Second, IAM damage functions tend to treat the world as nearly homogeneous, aggregating the globe into at most sixteen regions. This is important because nonlinearities in the relationship between temperature and human well-being are obscured by aggregation. For example, a given increase in temperature will have very different impacts in Arizona than it will in Minnesota, but this is missed when the United States is a single unit of observation. For both reasons, these damage functions have been heavily criticized in recent years (Pindyck, 2013).

2010 IWG Approach: In 2010, IAM damage functions were the only feasible option, and the IWG kept the damage functions originally developed in DICE, FUND, and PAGE.

Progress: In the last dozen years, advances in computing power, access to data from around the world, and econometric methods have led to an explosion of empirical research that has greatly deepened understanding of the economic impacts of climate change (Carleton and Hsiang, 2016). Now, there is almost an embarrassment of riches; for example, in a review of the literature we found 433 empirical studies on climate change's economic impacts that were published between 2010 and 2021 alone.

How should one choose among these studies when developing an updated damage function? To make full use of scientific advances, we believe that any modern damage function should meet three criteria:

1. **Empirically derived and plausibly causal:** Damage functions should be derived from empirical estimates that reflect plausibly causal impacts of weather events on socioeconomic outcomes.

Because the climate has remained stable throughout modern human history, experimental variation in the long-run climate is unavailable. However, a large and growing empirical literature leverages modern econometric methods to uncover causal impacts of short-run weather events on many socioeconomic outcomes, from agricultural output to mortality rates (Carleton and Hsiang, 2016; Dell et al. 2014). When combined with empirical estimates of differences in populations' responses to weather events (discussed below), this literature provides a strong foundation for understanding the socioeconomic effects of climate change (Hsiang, 2016).

The IAM damage functions used by the IWG do not meet this criterion. They are only loosely calibrated to empirical evidence and/or rely on outdated estimates that fail to isolate the role of climate from correlated variables such as income and institutions. For example, FUND's damage functions rely on associational studies published prior to 2000 that likely confound temperature with other factors. Similarly, early versions of the DICE damage function were only weakly tied to empirics (Diaz and Moore, 2017; Nordhaus, 2010), while the recent DICE update relies on associational evidence (Nordhaus and Moffat, 2017).

2. **Capture local-level nonlinearities for the entire global population:** Damage functions should be estimated with data representing the entire global population (not just high-income, temperate regions). Further, damage functions should account for nonlinear effects of climate variables at a local level.

Recent research estimates climate change's impacts on social and economic conditions at local scales across the globe. This work has uncovered a strongly nonlinear relationship between many socioeconomic variables and climate variables—that is, the effects of climate change are not identical everywhere. For example, extreme cold and extreme heat increase mortality rates, while moderate temperatures have little impact (Deschênes and Greenstone, 2011). This research has additionally documented large differences in climate impact relationships between rich and poor (Davis and Gertler, 2015), hot and cold (Heutel et. al., 2017), and agricultural and non-agricultural regions (Cai et al., 2016). These significant differences across different places imply that the additional damage caused by a given increment of warming depends on characteristics of the local economy, demographics, and region.

Existing IAM damage functions fail to adequately characterize nonlinearities, to disaggregate impacts locally, or to include information from lower-income, hotter regions of the globe. For example, the PAGE damage function is calibrated using data only from the United States (Cline, 1992). Similarly, the FUND mortality-specific damage function draws on multiple studies, only one of which (Martens, 1998) leverages mortality data, and only from Los Angeles, New York, Tokyo, Israel, the Netherlands, Taiwan, and the United Kingdom. None of these locations have the combination of a hot climate and low incomes that characterize the regions where several billion people currently live. Moreover, these models divide the globe into at most sixteen distinct regions, missing important spatial detail.

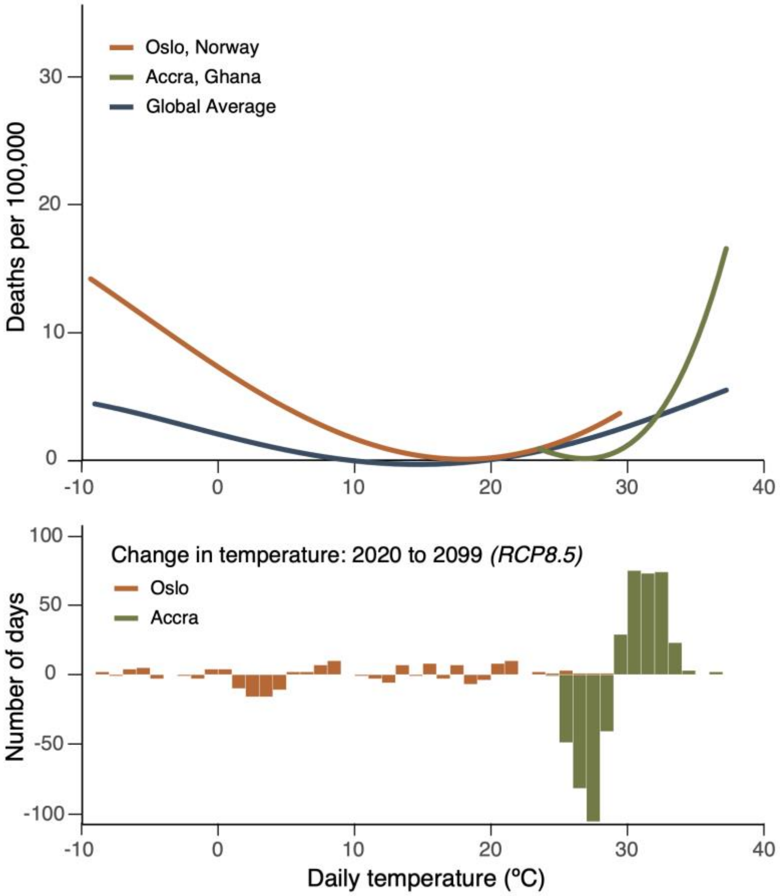

Figure 4: Climate change will have disparate impacts on different geographic regions. Figure displays estimated mortality-temperature relationships for ages >65 years (top panel), along with anticipated changes in the temperature distribution from climate change (bottom panel), for Oslo, Norway (orange) and Accra, Ghana (green). The top panel includes an average mortality-temperature relationship (blue), estimated using subnational data from 40 countries. In the bottom panel, the difference between the 2099 and 2020 temperature distributions is shown, using a high-emissions scenario (RCP8.5) from the CCSM4 climate model. Top panel relationships are only shown for the range of temperatures projected to be experienced in each location between 2020 and 2099. *Source:* Carleton et. al., 2021.

Figure 4 illustrates that failing to capture globally representative, locally varying, nonlinear relationships threatens the validity of damage functions. The top panel depicts distinct estimated mortality-temperature responses for Oslo, Norway, Accra, Ghana, and the global average (see Carleton et al. 2021 for estimation details). In the bottom panel, the differences between the 2099 and 2020 temperature distributions, assuming a high emissions scenario, are shown for Oslo and Accra. In Oslo, climate change is likely to save lives, as the mortality rate is highly sensitive to cold. In contrast, low incomes in Accra lead to extremely high mortality-sensitivity to heat, and large increases in heat-related mortality under climate change. It is also apparent that the global average mortality-temperature response function is a poor representation of the impact of climate change in both Oslo and Accra. Ignoring such differences by applying the global response function to both locations would substantially misrepresent climate change impacts. The broader point is that recent research has removed the need to apply highly aggregated empirical relationships to the entire world uniformly.

3. **Inclusive of adaptation:** Damage functions should reflect that people, firms, and governments make costly defensive investments to protect against climate-related risks.

As climate change unfolds, individuals, governments, and firms will make innumerable decisions and investments in response to the gradually changing environment. Damage functions within DICE, FUND, and PAGE involve very different assumptions about such compensatory investments and their costs, the majority of which are empirically unfounded (Diaz and Moore, 2017).

Damage functions should include both the estimated benefits and costs of future adaptive investments. While earlier empirical studies failed to account for adaptation benefits (e.g., Deschênes and Greenstone, 2007), a growing literature is developing damage estimates that reflect these benefits by quantifying how populations' responses to weather events vary with their average climate (e.g., Auffhammer, 2018; Deryugina and

Hsiang, 2017; Heutel et al., 2017). However, these compensatory investments are not free—updated damage functions should also account for adaptation costs.[5] Some progress has been made to infer these costs from available data (Carleton et al., 2021), but this is an active area of research.

Estimated damage functions that meet the above criteria lead to substantially different understandings about the economic impacts of climate change, compared to older damage functions. For example, one recent study estimated a mortality-only SCC that is more than ten times larger than the mortality SCC within FUND (Carleton et al., 2021). Further, its estimate of the loss from higher mortality rates in 2100 accounts for 49-135 percent of *total* damages across all sectors from the three IAMs. Another recent study derived an agricultural damage function that meets some (but not all) criteria above and found a substantial, positive, agriculture-only SCC, while FUND's agricultural SCC is negative (Moore et. al, 2017) (Figure 1).

Meeting these criteria does not always increase estimated damages. For example, one recent study estimated an energy-only SCC of -$2. This finding was attributable largely to net savings from reductions in heating and differences in the responsiveness of electricity demand to high temperatures in high- versus low-income regions of the world (Rode et al. 2021a). In contrast, the FUND model's energy-only SCC is $8 and constitutes 90 percent of the total, all-sector SCC (Diaz, 2014).

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[5] Adaptation cost estimates are important when computing total damages of climate change. In contrast, under a strict set of assumptions, the marginal benefits and marginal costs of additional adaptation cancel each other out in the calculation of the damages from a marginal ton of CO_2 emissions, making adaptation cost estimates unnecessary for the SCC when these assumptions are made.

These examples demonstrate that research that meets the three criteria described here lead to very different estimates of the economic impacts of climate change.[6] Of course, damage estimates that meet these criteria are not currently available for all sectors affected by climate change. While we discuss this challenge in detail in Section III and Supplementary Materials S.III, it is worth noting that many difficult-to-quantify sectors, such as ecosystem services and human migration, remain overly simplistic or absent in the IAMs as well (Kopp and Mignone, 2012) and others are only included with very ad hoc approaches.

Recommendation: **We recommend that all existing IAM damage functions be replaced with those that meet the above three criteria.**

Ingredient Three: Discount Module

Background: A single additional ton of CO_2 emissions causes a trajectory of additional warming, and a stream of future benefits and damages. The final SCC calculation step is to express the stream of net damages as a single *present* value, so that the present value of all costs and benefits can be calculated. The "discount rate" is the interest rate used to convert future impacts into present day dollars. Because CO_2 emissions lead to climatological shifts that last multiple centuries, small differences in the choice of discount rate compound over time, leading to meaningful differences in the SCC.

There are two reasons for discounting future monetary amounts. The first is that an additional dollar is worth more to a poor person than a wealthy one, which is referred to as the *declining marginal value of consumption*. The relevance for the SCC is that damages from climate change

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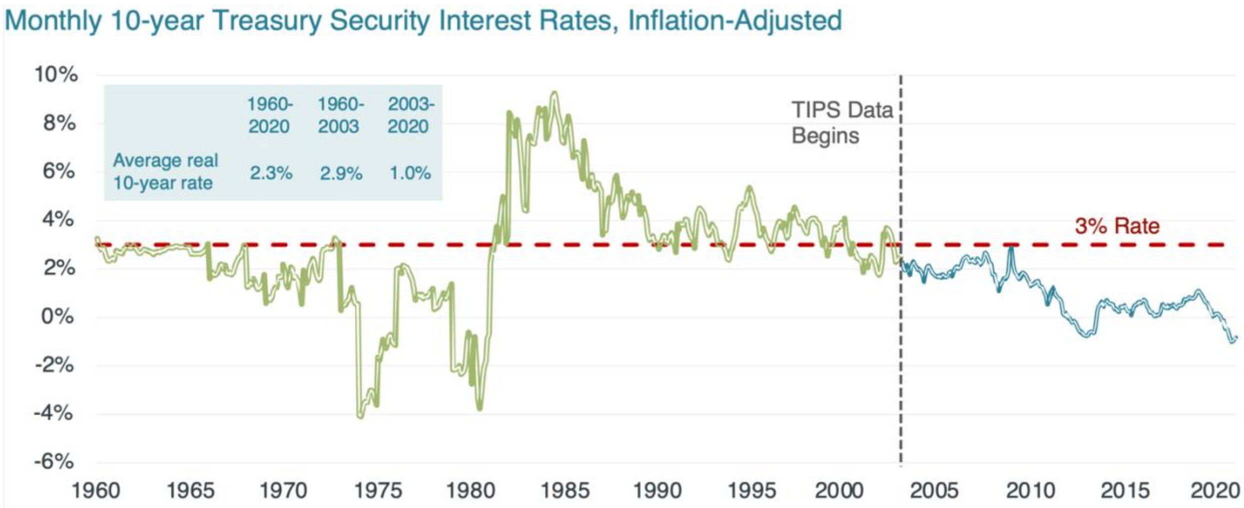
[6] Another approach to updating damage functions guided by the three listed criteria is "top-down" in nature, relying on statistical relationships between GDP and climate variables (generally, temperature) to quantify the impacts of climate change on aggregate growth in (or levels of) income (e.g., Burke et al. 2015; Dell, et al. 2012). We discuss the merits and challenges of using a top-down approach to inform damage functions in Supplementary Materials S.II.

that occur in the future will matter less to society than those that occur today, because societies will be wealthier. The second, which is debated more vigorously, is the *pure rate of time preference*: people value the future less than the present, regardless of their income. While some argue that the future should be treated equally to the present (e.g., Arrow et al., 1996), one explanation for a nonzero pure rate of time preference is the possibility of a disaster (e.g., asteroids or nuclear war) that wipes out the population at some future date, removing the value of any events that happen afterwards.

In general, U.S. government agencies have followed the Office of Management and Budget's (OMB's) recommendations in Circular A-4, which guides cost benefit analysis across the U.S. government, and used 3 percent and 7 percent discount rates in cost-benefit analysis (OMB, 2003). These two values are justified based on observed market rates of return: the 3 percent discount rate is a proxy for the real, after-tax riskless interest rate associated with U.S. government bonds and the 7 percent rate is intended to reflect real equity returns like those in the stock market. However, climate change involves intergenerational tradeoffs, raising difficult economic, scientific, philosophical and legal questions regarding equity across long periods of time. There is no scientific consensus about the correct approach to discounting for the SCC (Gollier and Hammitt 2014).

2010 IWG Approach and Progress: There are two possible approaches to discounting in SCC calculations. First, a "descriptive" discount rate can be used that is derived from observed interest rates. The 2010 IWG used fixed discount rates of 2.5 percent, 3 percent, and 5 percent, while the Trump Administration applied 3 percent and 7 percent. The 2010 IWG set 3 percent as the central case to be consistent with guidance from the OMB that was motivated by a 2003 calculation of the real interest rate on U.S. government ten-year bonds. This decision was also motivated by asset pricing theory and the assumption that climate damages are uncorrelated with overall market returns (Greenstone et al., 2013).

There have been profound changes in global capital markets since the publication of Circular A-4 in 2003 that make it challenging to justify 3 percent as an accurate estimate of the real return on riskless investments. For example, the average ten-year Treasury Inflation-Indexed Security (TIPS) rate since its inception (2003-present) is just 1.01 percent (Figure 5). Similarly, Bauer and Rudebusch (2020a,b) show that the equilibrium real interest rate has declined substantially since the 1990s. Additionally, evidence from long-term real estate investments suggests that for climate mitigation, which has payoffs over very long periods of time, discount rates should be even lower than those used to for shorter-lived investments (Giglio et al., 2015). Overall, our judgement is that it is difficult to defend a 3 percent discount rate for climate investments and there is now a compelling case for a riskless discount rate of no higher than 2 percent.[7]



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[7] Even without updating the calculation of the 10-year Treasury rate, a fixed rate below 2 percent does not contradict OMB Circular A-4 when long-lived benefit streams are under consideration: “If your rule will have important intergenerational benefits or costs you might consider a further sensitivity analysis using a lower but positive discount rate in addition to calculating net benefits using discount rates of three and 7 percent” OMB (2003). Supporting this conclusion, Sunstein (forthcoming) argues that a “decision to use a low discount rate, such as two percent, would be straightforward to defend against an arbitrariness challenge” (page 6).

Figure 5: Monthly 10-year inflation-adjusted Treasury security interest rates. Figure shows monthly 10-year Treasury security interest rates, adjusted for inflation, from 1960 to 2020. Nominal interest rates, Treasury Inflation-Indexed Security (TIPS), and inflation data were retrieved from the Federal Reserve Bank of St. Louis. The TIPS rate is available starting in January 2003. Interest rates prior to 2003 are imputed by subtracting the annual inflation rate from the nominal interest rate.

It is also possible, however, that the riskless rate itself is not appropriate as the central discount rate due to the unique risk properties of climate change and uncertainty about future interest rates. Because SCC discount rates reflect the returns to investments that mitigate climate change, Americans are best served by using an interest rate associated with investments that match the structure of payoffs from climate mitigation. Capital asset pricing models recommend discount rates below the riskless rate when investments (i.e., CO_2 mitigation) pay off in "bad" states of the world—that is, if climate damages are likely to coincide with a slowing overall economic growth rate due, for example, to "tipping points" (Greenstone et al., 2013). If on the other hand climate damages act as tax on the economy (i.e., total damages are larger when the economy grows faster), then higher discount rates like the average return in equity markets would be merited.

Finally, we note that the descriptive approach can accommodate a declining discount rate as recommended by Gollier and Weitzman (2010) to account for uncertainty about future discount rates. Thus, the descriptive approach could involve the pegging of the discount rate to an observed interest rate with a pre-determined declining schedule, although important implementation questions remain unsettled (e.g., Newell and Pizer, 2003; Cropper et al., 2014).[8]

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[8] The declining discount rate literature generally assumes that climate damages are uncorrelated with the discount rate (Cropper et al., 2014), which is limiting given the risk properties of climate change discussed above.

A second approach to deriving a discount rate is to explicitly account for future economic growth using the so-called Ramsey equation (Ramsey, 1928). This is referred to as the prescriptive approach and is recommended by the NASEM as "feasible and conceptually sound" (NASEM, 2017). Rather than rely on observed interest rates, it derives a discount rate from assumptions about three parameters: the pure rate of time preference, the growth rate of consumption, and a parameter capturing the decreasing marginal utility of consumption. Values for the first and third parameters have been estimated in large literatures (Gollier and Hammitt, 2014), while the consumption growth rate will depend on the scenarios developed in the socioeconomic and emissions module described below.[9]

Extensions of the Ramsey approach can accommodate covariance between climate damages and the level of future economic growth, as well as uncertainty in future economic growth (NASEM, 2017). The former is important given the risk properties of climate change discussed above. The latter is important because future growth is inherently uncertain; the 2017 NASEM report provides extensive implementation details for Ramsey discounting under uncertainty.

Despite the theoretical justification for a Ramsey approach, Circular A-4 explicitly instructs the use of constant discounting in cost-benefit analysis (OMB, 2003). Additionally, the Ramsey approach requires several judgments about the value of key parameters, rather than relying on observed market interest rates, giving policymakers a possibly undesirable degree of discretion.

Recommendation: **We recommend continuing to rely on existing asset markets to guide the discount rate choice. Based on recent trends, we recommend a discount rate of no higher than 2**

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[9] The Ramsey equation expresses the discount rate as $r = \delta + \eta \times g$, where δ measures the pure rate of time preference, g measures the growth rate of consumption, and η captures the decreasing marginal utility of consumption. The consensus is that δ likely ranges between zero and two. Values for η have been estimated in a large literature, and range from one to four, but are generally centered around two (Gollier and Hammitt, 2014).

percent. When applied to the original IWG SCC framework, a discount rate of 2 percent raises the SCC to $125 in 2020 (NYSERDA & Resources for the Future, 2020).[10]

Ingredient Four: Global or Domestic Damages

Background and 2010 IWG Approach: Traditionally, regulatory cost-benefit analyses only consider the domestic benefits and costs of policies. However, unlike nearly every other environmental pollutant, CO_2 emissions are a global problem. The damages caused by carbon emissions in the United States are felt globally, while Americans benefit equally from emissions reductions in China, the European Union, India, and Detroit. In light of the global nature of the problem, and as a means to obtaining foreign emissions reduction commitments in international negotiations, the IWG used global damages to calculate the SCC. In 2017, the Trump Administration began counting only domestic damages in the SCC.

Progress: While the question of global versus domestic damages involves economic, legal, and ethical nuance (Gayer and Viscusi, 2016), the consensus amongst scientific, economic experts, and international negotiators is that the SCC should include global damages (NASEM, 2017). Although focusing exclusively on the domestic costs of climate change may appear to put U.S. interests first, a growing body of evidence demonstrates the opposite. Nearly 90 percent of global emissions take place abroad, and history shows that when the United States accounts for the full global cost of climate change, it incentivizes other countries to reduce their own emissions. Some nations simply borrow the U.S. SCC. Further, the U.S. use of a global SCC plausibly contributed to international action. For example, in 2014 the U.S. EPA proposed the Clean Power Plan, and within four months China promised to make significant emissions reductions (Greenstone, 2019). Similarly, it is estimated that the United States was able to

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[10] This value has recently been applied across New York state agencies.

leverage 6.1-6.8 tons of CO_2 reductions from other countries for every ton that it pledged to cut in the Paris Climate Agreement (Houser et al., 2021).

In summary, the global SCC helps to overcome what might be seen as a classic prisoner's dilemma (see Kotchen, 2018). Moreover, because of the international nature of CO_2 as a pollutant, and hence the dependence of US citizens' welfare on emissions reductions abroad, a domestic-only SCC could be difficult to legally defend against an arbitrariness challenge (Sunstein, forthcoming).

Our recommendation is to use global damages in calculating the SCC, even though it is standard in many regulations to use only domestic measures of costs and benefits. Doing so is very likely to incentivize emissions cuts abroad, which benefits U.S. citizens, while ensuring the SCC is legally durable.

B. Additional Scientific Advances

Ingredient Five: Socioeconomic and Emissions Module

Background: In the SCC calculation, a baseline trajectory of economic growth and CO_2 emissions is compared to a trajectory in which one more ton of CO_2 is released. Due to nonlinearities in the relationship between emissions and climate change damages (i.e., a marginal emission does more damages at higher temperatures), higher baseline CO_2 emissions will result in a greater SCC. In contrast, baseline economic growth affects the SCC in a variety of competing ways. Richer economies generate higher emissions, so marginal tons do more damage, increasing the SCC. That said, richer countries are better prepared to invest in adaptations—such as increased air conditioning—that reduce the impacts of climate change. Changing demographics can also alter the SCC by, for example, increasing population levels and raising the share of the population at higher risk of heat-induced mortality.

2010 IWG Approach: The IWG combined five socioeconomic and emissions trajectories developed by the Stanford Energy Modeling Forum (EMF-22). Four scenarios represented business-as-usual trajectories, while one assumed that aggressive climate policies dramatically reduced future emissions. The IWG calculated the SCC under all five scenarios and averaged the result, giving equal weight to each scenario. These scenarios were overly simplistic (for example, assuming that economic growth declines linearly to zero by 2300) and they lacked transparent documentation and justification for key assumptions (NASEM, 2017).

Progress: There has been some scientific progress in this area, although it remains difficult to make long-run population and economic growth projections and to account for associated uncertainty. The IPCC and many researchers have moved towards using the Shared Socioeconomic Pathways (SSPs) as benchmark scenarios (Riahi et al., 2017). Appealingly, the SSPs can be linked to the Representative Concentration Pathway (RCP) emissions scenarios, a standardized set of widely used emissions trajectories.

However, these scenarios do not systematically characterize uncertainty. Economists have recently developed more sophisticated modeling techniques that rely on historical data to generate probabilistic economic projections (e.g., Müller et al., 2019) and demographers have done the same for population (United Nations, 2019). These empirically based projections can also be combined with expert elicitation to represent additional sources of uncertainty (NASEM, 2017).

Recommendation: **Our recommendation is to rely either on a combination of the SSPs and the RCPs *or* on new probabilistic projections that combine statistical methods with expert elicitation.** Projection probabilities should be chosen to best represent the most *likely* future global pathway.

Ingredient Six: Valuing Uncertainty about Climate Risk

Background and 2010 IWG: The SCC calculation involves several sources of uncertainty, including uncertainty about future economic growth, temperature sensitivity to additional emissions, and the economic damages for a given level of climate change. Economic theory and empirical evidence (e.g., the general existence of the insurance industry) reveal that people dislike risk and are willing to pay to reduce their exposure to it. The IWG did not account for uncertainty in valuing climate damages (effectively assigning zero value to risk) but noted that this decision "demands further attention" (Greenstone et. al, 2013).

Progress: Economic theory and empirical research decisively support the idea that people are risk-averse and value reducing uncertainty. In the last decade, advances in computing have enabled probabilistic climate change projections that capture multiple measures of uncertainty about the magnitude of climate damages. Thus, it is now possible to characterize these uncertainties and incorporate them into SCC calculations. For example, Rode et al. (2021a) estimate the total change in energy expenditures under climate change, accounting for climatological uncertainty and statistical uncertainty. Carleton et al. (2021) and Rode et al. (2021b) provide the analogous information for mortality and labor supply, respectively. A large theoretical literature demonstrates that valuing this uncertainty when individuals are risk averse can substantially increase the SCC (e.g., Lemoine, 2021; Jensen and Traeger, 2014). The application of standard methods of uncertainty valuation to empirically derived probabilistic damage estimates is an active area of research and is discussed in detail in Section III.

We recommend that the calculation of the SCC use standard economic tools for valuing the considerable uncertainty about damages from multiple sources.[11] Placing zero value on the

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[11] Specifically, this should be done by accounting for risk aversion using standard parameterizations of the shape of the utility function (e.g., $\eta = 2$ in a constant relative risk aversion utility function) from the existing literature to

uncertainty around climate damages runs counter to individuals' demonstrated dislike of risk as well as basic economic principles.

Ingredient Seven: Equity

Background: An additional dollar is worth more to a poor person than a wealthy one. Applying this principle to the SCC would require "equity weighting" within the United States such that a given amount of climate damages projected to occur in poorer counties or states of the United States contribute more to the SCC than equal damages that occur in wealthier regions. Indeed, this idea is the basis for the environmental justice movement in the United States. Taken one step further, this logic would mean that damages occurring in poor countries are weighted more highly than damages in wealthy countries.

2010 IWG Approach: The IWG chose to omit equity weighting, citing theoretical and practical concerns. Theoretically, the IWG determined the economic literature on equity weighting was insufficiently mature. Practically, the IWG determined that standard operating procedure for the U.S. government requires separate distributional analyses of policies, rather than incorporating distributional concerns into cost-benefit analyses (Greenstone et al. 2013).

Progress: The same logic that justifies discounting and the valuation of uncertainty over future states of the world implies that equity weights should be applied in SCC calculations; declining marginal value of consumption is the fundamental economic concept behind all three concerns. Therefore, the most intellectually coherent approach would be to calibrate equity

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determine the "certainty-equivalent" value of damages under climate change (Traeger, 2014). A "certainty-equivalent" value is computed by determining the consumption loss that society would accept as a certain outcome in place of the distribution of future uncertain outcomes.

weights from the large literature studying the marginal value of consumption, and to apply these weights at the spatial resolution of damages.[12]

However, OMB Circular A-4 (OMB, 2003) does not clearly allow for equity weighting within cost benefit calculations. Therefore, conducting equity weighting would represent a significant departure from standard U.S. cost benefit analysis, though not legally infeasible (Sunstein, forthcoming). Further, it would have precedential implications beyond climate regulations and environmental policy and would depend on a particular specification of a utility function.

Despite the challenges to equity weighting, new, local-level climate change damage estimates enable presentation of distributional impacts alongside the SCC even if equity weights are not applied in the SCC calculation. For example, Figure S3 shows new projected mortality risk estimates for 25,000 global regions. These projections can, for example, be used to characterize how climate damages vary with geography, income, race, and other factors both within the United States and globally. Inclusion of this distributional information will enable equity considerations to inform decision-making without imposing a particular utility function.

We recommend that information on the distributional impacts of climate damages be presented alongside the SCC, but that equity weighting not be incorporated into the SCC until there is an overhaul of Circular A-4. Such a review would allow for full consideration of the implications across multiple domains.

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[12] Standard parameterizations of utility function curvature (e.g., $\eta = 2$ with constant relative risk aversion utility) can be used to calibrate equity weights.

III. An Implementation Pathway for an Updated SCC

In summary, returning the SCC to the scientific frontier requires using an updated climate model, a new set of damage functions, a lower discount rate, and global damages. Updates to the other three SCC ingredients would be valuable, but our view is that they are judgment calls that turn on several factors including scientific and/or economic evidence and political considerations like precedential effects on regulatory policy in other domains. Among these other ingredients, however, there is an especially strong analytical (and perhaps legal) case for valuing the substantial uncertainty around climate damages.

The integration of these improved SCC ingredients necessitates choosing an implementation pathway. One approach would be to update each of the SCC ingredients *within* the three existing IAMs, wherever possible, and then use these models to produce new SCC distributions. While this may seem appealing due to historical precedent, there are conceptual and practical challenges to incorporating new damage functions into the existing models, which means that this approach would not reflect the full range of scientific advances in each SCC ingredient. These challenges include: lack of correspondence between empirically founded, sector-specific damage functions and IAM damage functions, making it difficult to know which sectors in the current IAMs to replace with new empirically-founded evidence; low spatial resolution in existing IAM damages, making it impossible to characterize inequities; inconsistent treatment of adaptation across models, making it difficult to match adaptation assumptions with empirically founded approaches to estimating adaptation; and legal risks raised by an inability to fully remove the ad-hoc assumptions in old models (Sunstein, forthcoming). Additionally, these IAMs prevent the IWG from fully implementing valuation of uncertainty (Ingredient Six) and equity (Ingredient Seven). These issues are discussed in greater depth in Supplementary Materials S.III.

Therefore, we believe that returning the SCC to the frontier of understanding and ensuring its legal durability requires constructing a new SCC framework. Notably, such a change is also consistent with the NASEM (2017) recommendation for a new IAM. From a practical standpoint, the form of a new SCC framework depends on the degree to which the current OMB Circular A-4 remains in force. The following section describes a pathway for a holistic update to the SCC with the current version of a Circular A-4. We then summarize how this pathway could evolve under an updated Circular A-4, providing details in Supplementary Materials S.IV.

Building a new IAM under the current Circular A-4

We recommend that a new IAM be built in which each module directly follows the above recommendations for each of the seven SCC ingredients. Such a new framework is under development by the Climate Impact Lab (CIL),[13] of which both authors are core members, and will be released in Fall 2021 (Nath et al., 2021). The CIL combines SSP socioeconomic projections (and can accommodate others), high-resolution climate projections for multiple RCP emissions scenarios, and comprehensive historical datasets to estimate sector-specific, flexible, globally representative damage functions that capture heterogeneity across 25,000 regions and account for adaptation and its costs. It then applies the climate model FAIR and a range of valuation and discounting approaches to transform these damage functions into a distribution of SCC estimates, accounting for and valuing multiple sources of uncertainty. Under this pathway, the distributional consequences of climate change would be reported alongside the SCC, enabling equity considerations to play a role in decision-making even if equity weights are not applied to the SCC.

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[13] The Climate Impact Lab is a collaboration of climate scientists, economists, computational scientists, and students working to build an empirically-based SCC. More information at http://www.impactlab.org/.

This approach has strengths and weaknesses. A great appeal is that all seven ingredient recommendations can be followed. An additional strength that bears underscoring is that it allows for characterizing the distributional effects of climate policies for localities and demographic groups within and beyond the United States.

On the other hand, a key weakness is that damage functions meeting the above criteria are not currently available for all sectors affected by climate change. This new IAM will become more complete as science and economics advance, but in the medium term, the resulting SCC will be based on incomplete damage estimates. Although this is an important shortcoming, many key areas of incomplete knowledge—such as difficult-to-quantify sectors, catastrophic risks, and interactions across regions and sectors—remain overly simplistic or absent in the IAMs as well (Kopp and Mignone, 2012; Supplementary Materials S.III). For example, in FUND, energy demand alone accounts for ~90% of the SCC (Diaz, 2014), implying many "modeled" sectors remain in practice unquantified. DICE includes a 25% damage adjustment for non-monetized impacts based on a "judgmental assessment" (Nordhaus and Moffat, 2017). In PAGE, catastrophic risks arise through an arbitrary and parametric damage discontinuity. In contrast, by building a new IAM based directly on the most credible sector-specific empirical evidence, adding new sectors to increase the comprehensiveness of the SCC will be straightforward. Similarly, updates to other modules, such as the climate model, are also easily accommodated.

Our conclusion is that a revised SCC should be fully based on empirical evidence that meets modern standards. While this approach may initially omit certain categories of damages, existing results suggest that even partial accounting of sector-specific damages is likely to raise the existing U.S. SCC (Figure 1), particularly if discount rates are updated and uncertainty is properly valued. Further, we think that the SCC's legal durability would be enhanced, as this approach reflects scientific advances over the past dozen years and is built to accommodate future advances.

Building a new IAM under an updated Circular A-4

If OMB Circular A-4 were updated to allow for more flexibility in the valuation of climate change damages, endogenous discounting (Ingredient Three) and the valuation of equity (Ingredient Seven) would be practically feasible. If this were to take place, we recommend that consideration be given to building a new IAM that follows the exact same SCC framework described above, but replaces constant discounting and no equity weighting with a flexible valuation approach that includes Ramsey discounting, equity weighting, and multiple treatments of uncertainty valuation. We detail the theoretical basis for this approach, its many variations, and its strengths and weaknesses in Supplementary Materials S.IV.

Assuming current Circular A-4 or something similar is in force, we recommend an updated SCC be developed based on a new IAM following the seven recommendations outlined in this paper. This pathway will deliver a transparent, internally consistent, and scientifically robust set of SCC estimates that can accommodate evolving research. With substantial changes to the United States Government's approach to cost-benefit analysis, and presumably to Circular A-4, we believe that alternative damage valuation options are feasible and should be carefully considered for adoption.

IV. Conclusion

This paper details a recipe to return the SCC to the frontier of climate science and economics. For the most part, our recommendations reflect conclusions reached almost five years ago in NASEM (2017) on how to update the SCC with the differences largely due to advances in understanding since its release (see Supplementary Materials S.V for differences in recommendations). Following these recommendations has economic and scientific merit and would enhance the SCC's legal durability.

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